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Comparison of speech recognition in noise using a frequency modulated (FM) system and wireless hearing aid accessory microphone signal (AMS)

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COMPARISON OF SPEECH RECOGNITION IN NOISE USING A FREQUENCY MODULATED (FM) SYSTEM AND WIRELESS HEARING AID ACCESSORY MICROPHONE SIGNAL (AMS)

by

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Abstract: A randomized investigation and comparison of the speech recognition in noise of hearing aid users using two different assistive listening devices

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Key Words: Reception Threshold for Sentences (RTS); Hearing In Noise Test (HINT); Acceptable Noise Level (ANL); Frequency Modulated (FM); Accessory Microphone Signal (AMS); Hearing Aid (HA)

Abbreviations: AMS = Accessory Microphone Signal; ANL = Acceptable Noise Level; ANOVA = Analysis of variance; BTE = Behind The Ear; BN = Background Noise; dB = Decibel; FM = Frequency Modulated; HA = Hearing Aid; HINT = Hearing In Noise Test; MIL = Most Intelligible Level; NAL-NL1 = National Acoustic Laboratories' – Nonlinear version 1 prescriptive target; NU-6 = Northwestern University Test Number 6; RTS = Reception Threshold for Sentences; SD = standard deviation; SLM = Sound Level Meter; SNR = signal-to-noise ratio; WRS = Word Recognition Score

INTRODUCTION

There are several environments in which recognizing speech can be difficult for people with hearing loss. For example, one of the most difficult environments to understand speech is in noise, even for people with normal hearing (Sperry et al, 1997). While listening in noise, it may only be possible to hear part of the speech signal. Therefore, recognition of speech sounds is based on only a portion of audible information (Neff and Green, 1987; Assmann and Summerfield, 2004; Parikh and Loizou 2005). To overcome some of the difficulty of communicating in the presence of background noise, the speaker can increase the volume of his voice (Lane and Tranel, 1971). However, this can place strain on the speaker's voice, increase the frequency of the signal, and distort the intelligibility of the message (Lazarus, 1990). Another environment that causes strain on a person's ability to communicate is within a large, reverberant room. In Payton et al (1994), increasing levels of reverberation negatively affected the ability of individuals with hearing loss to recognize speech. This degradation was also seen for people with normal hearing.

This comparison of noise and speech signals is commonly referred to as the signal-to-noise ratio (SNR) and is measured in decibels (dB). Noise is defined as any competing signal within an environment, such as air ventilation systems or other talkers. A quieter environment establishes a higher SNR, which indicates an easier listening condition. When a listener is physically further away from a talker, a lower SNR makes the desired message even more difficult to understand (Flexer, 2004). People with sensorineural hearing loss require a SNR of up to +20 dB for optimal speech recognition scores (Ross et al, 1991). Due to the fact that a majority of real-world listening conditions most commonly range from -10 to +5 dB SNR, the speech recognition ability of people with sensorineural hearing loss is often at a disadvantage (Ricketts and Hornsby, 2005).

People with sensorineural hearing loss have an impaired auditory system that cannot be restored with hearing aids (Corliss, 1967; Moore, 2008). This concept can be expressed through psychoacoustic tuning curves, which demonstrate the reduced temporal and spectral resolution of an impaired cochlea (Glasberg and Moore, 1990). A person with sensorineural hearing loss experiences increased difficulty in the capacity to recognize auditory messages, a barrier which has the potential to lead to social withdrawal and isolation (Arlinger, 2003). By providing amplification at the frequencies where a hearing loss exists, hearing aids can provide an improvement in the quality of life and ability to communicate (Kochkin, 1992; Weinstein, 1996; Kricos et al, 2007). Despite having appropriately fit hearing aids, a person with sensorineural hearing loss can still experience difficulty recognizing speech. Hearing aids alone do not solve all of the problems associated with recognizing speech, especially in the presence of background noise or in reverberant environments. In fact, they often offer very little improvement in the SNR when a hearing aid user is in a difficult listening situation (Crandell and Smaldino, 2000). Furthermore, algorithms used to predict speech recognition tend to overestimate this ability in degraded environments, such as in noise or in reverberation (Payton et al, 1994). Notably, these environments are two of the biggest obstacles for hearing aid users (Hawkins and Yacullo, 1984; Needleman and Crandell, 1995; Killion, 1997; Crandell and Smaldino, 2000).

In comparison to omnidirectional microphone technology, directional microphone technology has demonstrated significant improvements in speech recognition in difficult listening environments, especially in noise. This benefit has been found on the order of 3 to 4 dB (Hawkins and Yacullo, 1984) or as high as 7 to 8 dB (Valente et al, 1995). Directional microphones generally function best when the desired signal is directly in front of the hearing aid user at 0° azimuth, and the noise is directly behind the person at 180° azimuth. Additionally, directional microphones offer some degree of customization to the hearing aid user. For example, the beam of a directional microphone can be narrowed to focus on a desired signal. Additionally, the user can sometimes choose where to focus the microphone. Despite these advancements with directional microphone technology, understanding speech in the presence of background noise is consistently ranked as one of the most difficult listening situations for hearing aid users (Surr et al, 1978; Kochkin 1992; 1996; 2000; 2002; 2005).

In recent years, there has been little progress in extracting the desired speech signal from noise via purely acoustical analysis (Levitt, 2001). Noise reduction technology ideally amplifies all speech sounds and attenuates all non-speech sounds. However, this technology generally operates as a high-pass filter, and can eliminate both speech and noise from 400 to 1000 Hz (Levitt, 2001). It is impossible to amplify a specific speech signal without also amplifying undesired speech and/or noise that occurs within the frequency spectrum of the desired signal (Neuman and Schwander, 1987). Therefore, in a crowded restaurant where multiple conversations can occur, hearing aids alone sometimes do not adequately assist the hearing aid user enough to recognize the desired speech signal. Noise reduction technology has not been proven to provide a significant amount of improvement in speech recognition in noise; however, it has demonstrated an ability to improve the comfort level of the hearing aid user (Boymans and Dreschler, 2000).

If hearing aids alone cannot provide adequate benefit in noise or in reverberant rooms, then assistive listening devices (ALDs) may offer a way to improve the SNR for hearing aid users. There are several types of assistive listening devices available on the modern hearing instrument market. One of the most commonly used devices to improve the SNR is frequency modulated (FM) technology. An FM system includes a transmitter device that is placed at the location of the desired sound source. There is also a wireless receiver that sends the sound message to the hearing aids. The transmitter, also called a remote microphone, enables the hearing aid user to listen to the signal while minimizing the effects of background noise and reverberation.

FM technology has been commonly utilized with children in the school population (Hawkins, 1984; Nabelek et al, 1986; Flexer et al, 1989; Boothroyd and Iglehart, 1998). Children benefit from an FM system because the FM transmitter captures the teacher's voice and sends the speech directly to the receiver attached to the child's amplification device. Therefore, the physical distance between the child and the teacher does not interfere with the transmission of the signal over the noise in the classroom. The FM device allows for the equivalent hearing ability of a speaking distance between the child and teacher of 3-6 inches. By decreasing the distance that the desired speech travels, the SNR improves. Therefore, the listener experiences an improvement in speech recognition (Wertz et al, 2002).

Adults may also experience improved speech recognition in difficult listening situations with FM technology. Under laboratory conditions, the use of an FM system while in noise can result in performance equal to the speech recognition in quiet (Boothroyd, 2004). In field studies, the use of an FM system was most beneficial at a distance or in noise with one talker (Boothroyd, 2004). In Fabry (1994), SNR improvements with the use of an FM system were found to be 9-10 dB higher than with hearing aids (HA) alone. On the other hand, the use of a combined FM and HA resulted in a lower SNR which resulted in only 4 dB of improvement. In a more recent study, Lewis et al (2004) found much higher improvement with the use of an FM system. The use of a monaural FM system resulted in improvements over omnidirectional hearing aid microphone technology on the order of 15-20 dB. With the use of a binaural FM system, the improvement was even greater at levels of 18-22 dB. Additionally, the FM system was found to even outperform directional microphone technology (Lewis et al, 2004).

Finally, the FM system functions well in real-world listening conditions. For example, Thibodeau (2010) reported subjective feedback from participants who believed that speech sounded “clearer, louder, and easier to understand” while using an adaptive FM system. In Sanford and Kierkhaefer (2002), experienced adult hearing aid users who wore behind the ear hearing aids were asked to do a trial run with an FM system. They were asked to judge their hearing with their current hearing aids and then again with the FM system after three to five weeks. The largest improvements were seen in restaurants, lectures, in a car, and at a distance. Notably, at the end of this study, 20/28 of the participants elected to purchase an FM system. On the other hand, in Lewis et al (2005), adult participants who experienced speech recognition benefit with the FM system still did not wish to pursue purchasing an FM system. In Boothroyd (2004), it was also the case that no participants expressed an interest in purchasing an FM system. In Lewis et al (2005), no clinically significant improvements were noted with psychosocial function to correspond with speech recognition improvements. Instead, these participants preferred to use their hearing aids alone due to the expense, inconvenience, and cosmetically unappealing remote microphone.

Another ALD option to improve the SNR is a remote microphone that uses Bluetooth technology. Several hearing aid manufacturers have recently released products with this technology. A few examples include Phonak’s RemoteMic, Unitron’s UMic, and Starkey’s SurfLink Mobile. Many of the devices function not only as a remote microphone but also as a remote control, cell phone, or television streamer. When utilizing the remote microphone portion of this device, the accessory microphone system (AMS) aims to accomplish the same goals as the FM. However, the technology behind the two systems differs. There are, to the author's knowledge, no peer-reviewed journal articles examining the benefit of AMS. Furthermore, the author is unaware of any studies that compare the performance of hearing aid users' speech recognition in noise while using FM and AMS technologies. A modern FM system's cost to the patient is often in excess of two thousand dollars; on the other hand, AMS technology only costs the consumer several hundred dollars. If the AMS technology performs equally as well as an FM system, it could become a more affordable option for patients to purchase in order to improve their ability to recognize speech in noise.

Previous studies have examined the speech recognition of people with hearing loss while using hearing aids and assistive listening devices such as an FM system. To the author's knowledge, no study exists that explores speech recognition while using an AMS device. A study analyzing this could be especially beneficial because this technology offers the possibility for a hearing aid user to improve speech recognition in noise, similar to the FM technology. It is of interest to learn how the AMS contributes to the speech recognition ability of patients prior to fitting them in the clinic with such devices. The purpose of this study was to examine the speech recognition in noise of adult hearing aid users with a moderate to severe sensorineural hearing loss while using the AMS technology and thereafter to compare the results to the FM technology. The goals of the study are to evaluate:

1. If the AMS technology significantly differs from the FM technology's ability to improve speech recognition in noise using the Hearing in Noise Test (HINT) (Nilsson et al, 1994).

2. If there is any difference between the FM system and AMS device's tolerance of background noise using the Acceptable Noise Level (ANL) test (Nabelek et al, 1991).
3. Whether participants prefer the AMS device or the FM system according to a questionnaire that will be distributed post-test session.

It is hypothesized that no significant differences will exist between the FM and AMS systems for all measures. Although the two systems differ according to the type of technology that is used, the fundamental concept behind the two systems is the same. They both pick up a speech signal and deliver that signal to the hearing aids, which bypasses the distance between a speaker and a listener.

METHODS

Participants

Fourteen adults, six males and eight females, who ranged in age from 56 to 85 with a mean age of 72.9 (standard deviation (SD) of 9.8) were recruited for this study. All participants were current hearing aid users with a mean of 10.3 (SD=5.8) years of experience using hearing aids (Table 1). All participants were recruited from Adult Audiology at Washington University School of Medicine in St. Louis. Consent was obtained for two additional participants; however, they were excluded from the study because their hearing was outside of the candidacy guidelines at the time of the visit. This study was approved by the Human Research Protection Office at Washington University in St. Louis, and all participants signed an approved informed consent form. Participants were offered a package of batteries for their participation.

In order to determine the number of participants needed for this study, data from previous research studies was analyzed for hearing aids and for FM systems. Based on data from Lewis et al. (2004), a power analysis utilizing G*Power 3.0.10 software was performed. It was determined that three subjects were required to determine statistical significance based on the means (-1.1 and -18.0 for hearing aids only and FM system, respectively) and standard deviations (SD) (3.5 and 4.3 for hearing aids only and FM system, respectively), a correlation between means of 0.5, a two-tailed test, alpha of 0.05, and power of 0.80. Due to the fact that no peer-reviewed data exists on the AMS, there was a possibility that the difference between the means would be poorer than predicted, the SD would be greater than predicted, and/or the correlation between the means would be poorer than predicted. Therefore, this study aimed to recruit a higher participant number.

Mean pure-tone thresholds were consistent with a mild sloping to moderately-severe sensorineural hearing loss (Figure 1). Word recognition (WRS) test results revealed a mean score of 81% (SD=0.1) for the left ear and a mean score of 80% (SD=.01) for the right ear. All of the participants met the following inclusion/exclusion criteria:

1. between 30-85 years of age
2. Must previously have worn or currently wear bilateral behind-the-ear (BTE) hearing aids with a custom fit ear mold
3. Have ear canals free from cerumen and debris
4. Bilateral, symmetric sensorineural hearing loss ≥ 20 dB HL and ≤65 dB HL from 250 to 500 Hz and hearing loss ≤75 dB HL from 1000 to 4000 Hz
5. Word recognition scores ≥ to 60%
6. No asymmetrical hearing losses consisting of differences of 15 dB HL at three neighboring frequencies, 20 dB HL at two neighboring frequencies, or 25 dB HL at one frequency

7. Cannot have a pacemaker.

Equipment and Calibration

A single-walled sound suite located within an acoustically-treated room was used for the testing. Two portable Anchor Audio AN-130 loudspeakers were each positioned on top of adjustable tripods. The tripods were adjusted so that the height of each of the loudspeakers on the tripod was measured at a height of 44 inches and were 54 inches from the center loudspeaker. The center speaker was a non-portable speaker attached to the sound suite. Using a goniometer, the two side loudspeakers were measured at 90 and 270 degrees azimuth to the participant's head. A Larson-Davis 706 Type 2 dosimeter utilizing A-weighting was used for calibration of all three loudspeakers and is shown in Figure 2. Prior to the testing of participants, the dosimeter was calibrated using a 114 dB SPL 1000 Hz pure-tone using a Quest CA-12M calibrator. The ambient noise level within the sound suite was 38 dBA.

Loudspeakers were calibrated daily. Calibration involved placing the microphone of the sound level meter (SLM) on top of another tripod 54 inches away from the center loudspeaker at 0° azimuth and at a height of 34 inches from the seat of a chair positioned facing the center loudspeaker. Using the calibration tone of the Hearing in Noise Test (HINT) CD, the VU meter on the audiometer was set to 0. With the noise track on the HINT CD, the volume of the center loudspeaker was adjusted on the dial of the audiometer until the SLM measured a level of 65 dBA. Following this, each of the portable speakers was calibrated individually to approximately 62 dBA using the noise track of the HINT CD. The combined level of the two portable loudspeakers at 90 and 270° was +/-1 65 dBA. See Figure 3 for the setup of the test space. For the Acceptable Noise Level procedure in this study, the VU meter on the audiometer was calibrated, and the side loudspeakers were turned off.

Before the beginning of the research study, the audiometer was checked using a listening and linearity check. The dBA values were measured using 5 dB steps, and the corresponding dBA values confirmed a consistent correlation between the audiometer and the measured sound level, within +/-2 dB. Measurements were made from 30 dB HL up to 80 dB HL. Additionally, the critical distance was measured by projecting 65 dBA calibrated noise from the HINT CD. The microphone of the SLM was placed at 54, 27, 13.5, and 6.75 inches away from the loudspeaker. The level of the HINT noise increased by 8, 7, and 6 dBA, respectively. The linearity check and critical distance measurements were repeated toward the end of study. The linearity check measurements were made in the same manner as the initial measurements and confirmed a consistent correlation between the audiometer and measured sound level, within +/-2 dB. To perform the critical distance measurement, the SLM speaker was again placed 54, 27, 13.5, and 6.75 inches away from the speaker. The level of the HINT noise increased by 7, 6, and 5.5 dBA, respectively. All values were within +/-2 dB of the expected 7 dB level increase according to a halving of distance between the speaker and the projected noise.

Hearing Devices

All participants were fit bilaterally with Phonak Bolero Q-90 BTE hearing aids. Each participant used his or her own ear molds. The tubing attached to each of the ear molds was inspected for pliability and excessive moisture, and the ear molds were examined to ensure that they were clean and fit well inside the concha of each participant's ear. Ear molds were cleaned and tubing was changed as necessary, then the tubing and ear molds were attached to the research study BTE hearing aids. The FM system used in this study used binaural Phonak ML16i dynamic FM receivers, which were attached to the Bolero hearing aids (Figure 4). The FM transmitter used in this study was the Phonak Inspiro with an attached lapel microphone (Figure

5). The The AMS transmitter used in this study was Phonak RemoteMic (Figure 6), which requires the Phonak ComPilot (Figure 7) to operate. The ComPilot is an intermediary device that allows the RemoteMic to transmit signal information to the hearing aids.

Procedures

All participants were scheduled for a single two-hour session at the student lab at the Central Institute for the Deaf. Otoscopy was then conducted to visualize the ear canals. Pure-tone air conduction and word recognition thresholds were obtained bilaterally for all participants who had not received a hearing test within six months prior to the study visit. A GSI 61 Clinical Audiometer was used to obtain pure-tone thresholds at 250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz. The GSI 61 Clinical Audiometer was used along with a SONY Compact Disc Player CDP-591. To obtain WRS, the Most Intelligible Level (MIL) was found using the recorded Northwestern University Auditory Test Number 6 (NU-6) recorded word lists using a female speaker (Tillman and Carhart, 1996). If a participant's most recent test was within the past six months, the results from that test were used. Additionally, these participants verbally affirmed that they did not believe that their hearing levels had changed since the test date.

If the participant still met the study's criteria, participants were fit with bilateral Phonak Bolero Q90-P hearing aids. The participant's ear molds were attached to the research hearing aids, and a feedback test was performed. To fit the hearing aids according to NAL-NL1 (National Acoustics Laboratory-Non Linear 1) real-ear insertion was performed. A probe tube microphone coupled to a Frye FONIX 8000 Hearing Aid Analyzer was measured and inserted into the ear canal approximately 2-5 millimeters from the tympanic membrane. Corrections were made for binaural and channel summation (18+ channels). A digitized speech composite signal was presented at 0° at levels of soft, average, and loud speech, 50, 65, and 80 dB SPL, respectively. The output was measured in the ear canal and NAL-NL1 targets were matched within +/-5 dB SPL from 500-4000 Hz by making appropriate adjustments within the fitting software (Figure 8). SoundRecover was turned off, but all other settings remained at the default values within the Phonak fitting software, Phonak Target™. The FM program was added under "additional programs," and the ComPilot settings were saved under an automatic Bluetooth program. The Bluetooth and FM programs were copied from the default speech in noise settings. However, adjustments during real-ear measurement were applied to all programs.

The FM and AMS settings were examined utilizing test box speech mapping measures on the AudioScan Real-Ear Hearing Aid Analyzer. To do this, a 65 dB SPL input was measured inside the test box for a total of four conditions: with the hearing aid, with the hearing aid while the FM system was turned off, with the FM, and with the AMS. Several attempts were made to verify the FM and AMS system this using the Frye 8000; however, none of the signals used with the Frye 8000 delivered a frequency response that could replicate the output of the hearing aids. The method of verification used in this study is known as the "transparency approach" (American Academy of Audiology, 2007a, 2007b). The frequency output for participant number seven is shown in Figure 9. Traditionally, this method has been utilized for the verification of the FM system in order to ensure that the FM follows the frequency output of the hearing aid within +/-2 dB. Currently, there have been no established verification procedures for the AMS; therefore, the FM verification procedure was duplicated with the AMS for this study. Adjustments to the volume were made to the FM device via the Inspiro as necessary in order to ensure as similar outputs as possible between the hearing aid and FM system. In order to establish the first fit levels of the AMS verification was completed for the RemoteMic. All settings of the RemoteMic were maintained at default position.

Test Stimuli

Following the verification of the hearing aids (HA), FM system, and AMS, each participant was repositioned in the sound booth to sit in a chair at 0°to the center loudspeaker. Each participant completed a HINT in three conditions: hearing aids only, hearing aids with the FM system, and hearing aids with the AMS. The order of the conditions as well as the sentence presentation order of the HINT material was randomized prior to testing using a randomizer (Urbaniak and Plous, 2013). The HINT is a standardized and recorded test that can be used to estimate the signal-to-noise ratio (SNR) at which the sentences embedded in background noise can be repeated correctly 50% of the time. It can objectively evaluate hearing aid patient success (Vermiglio, 2008). The volume of sentence presentation was increased by 4 dB until the sentence was correctly repeated by the participant. A process of raising or lowering the presentation level occurred thereafter according to a participant's correct or incorrect response of the test material. A step size of 4 dB was used up to fourth sentence and a step size of 2 dB was used after the fourth sentence.

The reception threshold for sentences (RTS) was calculated using this adaptive procedure for all three listening conditions. The level of the noise from the side loudspeakers remained constant at 65 dBA throughout the testing. A total of twenty sentences were completed for each condition plus the calculated intensity for a twenty-first sentence that is determined by the response for sentence 20. To complete the FM and AMS conditions, the remote microphones for each system were placed 7 inches away from the speaker. The manufacturer recommends that the remote microphone of the FM system be placed at a distance of 6 inches away from a signal and that the remote microphone of the AMS be placed at a distance of 8 inches away from a signal. A distance of 7 inches from the speaker was used for this study in order to minimize sound source to remote microphone differences between the FM and AMS while keeping the devices as close as possible to the manufacturer's recommended distances.

All participants also completed the Acceptable Noise Level (ANL) procedure (Nabelek et al, 1991). The ANL is used to evaluate a person's tolerance of noise, which is thought to be indicate of how will a person will be to wear a device. The idea behind the ANL is that some listeners will not be good candidates for a hearing device if they lack the ability to tolerate background noise. Those who are willing to tolerate more noise will likely be more successful hearing aid users. For this study, this premise was extended to the FM and the AMS in addition to recording the ANL with the hearing aids. The order of the conditions was randomized using the same method as for the HINT.

To complete the ANL, the volume of a recorded and standardized speech of a story was played through a loudspeaker. The volume was increased in 5 dB steps until the participant notified the tester that the level of the passage was "too loud". Then, the volume was decreased in 5 dB steps until the volume was "too soft". The volume was then increased in 2 dB steps until the passage was at a participant's "most comfortable listening level" (MCL). The level of the passage remained at this level for the next step of the ANL procedure. The participant then completed the same reporting for the level of the background noise, which was increased until the volume was "too loud," decreased until it was "too soft," and increased again to find a level that was the most he or she would "be willing to tolerate". This value is called the background noise level (BNL). The ANL was derived from calculating the difference of the background noise level from the level of the passage (MCL-BNL).

ANL scores have been described in three categories. Participants with a score that is less than 7 dB are likely to become successful and compliant users. Those whose score is greater than

13 dB are likely to have poor hearing aid compliance, and finally, participants whose score is between 7 and 13 have an unreliable device prediction. A score between 7 and 13 implies that the ANL does a poor job of predicting whether these people will become successful or unsuccessful hearing aid users.

All participants then completed a questionnaire regarding their opinions on the devices used in the study (Figure 10). The first set of questions aimed to find out with which of the devices the participants believed they heard the best. They had the option to rate understanding speech as “very”, “moderately”, “somewhat”, or “not” difficult. The participants then answered two open-ended questions: what they did or did not like about the devices, and if they would be interested in trying out any of the devices. Responses regarding the participants’ self-perceived speech recognition were tallied and grouped by device condition.

At the end of the test session, all participants’ ear molds were reconnected to their own hearing aids. All devices used for testing were cleaned in between test sessions using hospital-grade disinfectant wipes.

RESULTS

Hearing in Noise Test (HINT)

Mean RTS and ±1 standard deviation for each listening condition (HA, FM, and AMS) are reported in Figure 11. The mean score for the HA condition was 2.94 dB SNR (SD=4.57), -6.95 dB SNR (SD=4.85) with the FM system, and -14 dB SNR (SD=8.06) with the AMS. A repeated-measures analysis of variance (ANOVA) was performed and revealed that the mean differences in RTS (dB) were statistically significant across all three listening conditions $F(2, 26) = 41.3$, $p < .001$. Additionally, the partial eta-squared revealed that 76% of all variance was due to device variance, rather than intersubject or random variance. A pairwise comparison was performed across the three device conditions to reveal significance between devices. The HA condition performed significantly poorer than the FM condition ($p<.05$) with a mean difference of 9.89 dB SNR. The HA condition also performed significantly poorer than the AMS condition ($p<.05$) with a mean difference of 16.94 dB SNR. Finally, FM performed significantly poorer than the AMS condition ($p<.05$) with a mean difference of 7.05 dB SNR. Figure 12 shows the improvement seen over the HA condition with the FM and the AMS.

Acceptable Noise Level (ANL) Procedure

The ANL (in dB HL) for each listening condition was calculated by subtracting the BNL from the MCL for each participant. Mean and ± 1 standard deviation ANL values for each participant and are reported in Figure 13. A mean score of 11.14 dB (SD=9.21 dB) for the HA condition, a mean of 7.71 dB (SD=7.84) for the FM condition, and a mean of 11.57 dB (SD=9.32 dB) for the AMS condition were found. ANOVA was performed and revealed that the mean differences in RTS (dB) were not statistically significant across the three listening conditions $F(2, 26) = 1.12$, $p > .001$. A pairwise comparison was performed across the three device conditions and revealed no significance between devices. No statistically significant difference was found between the performance of the HA and the FM system ($p>.05$), nor between the HA and AMS ($p>.05$), nor between the FM and AMS ($p>.05$).

Verifit

Test box frequencies of 250, 500, 750, 1000, 1500, 2000, 3000, 4000, and 6000 Hz for each of the four test box conditions were measured: HA, HA (FM on), FM microphone, and AMS microphone. The verification technique used in this study requires that a hearing aid is run while the FM is turned on (American Academy of Audiology, 2007a, 2007b). Therefore, the statistical analysis includes measures from HA (FM on). However, no differences were expected between the HA and HA (FM on) conditions. Means and ±1 standard deviation for the left ear and all conditions are displayed in Table 2a. The means and ±1 standard deviation for the right ear and all conditions are displayed in Table 2a. All repeated measures ANOVA revealed statistical significance across all four device conditions. These values for the left ear can be found in Table 2b and for the right ear in Table 2b.

A pairwise comparison demonstrated the potential differences between each device condition. No statistically significant differences were revealed between the HA and HA (FM on) conditions for 250-6000 Hz for both the right and left ears. For both HA conditions and the FM, no differences were seen at 250 and 500 Hz for the right and left ears. At 750 Hz, a statistically significant difference was seen between the HA (FM on) and FM in the right ear only, with $p<.001$. The FM and AMS conditions were statistically significant from each other as well as from both the HA conditions from 1000-6000 Hz in the right ear, with $p<.001$. In the left ear, this was also found for 1000, 1500, 3000, and 6000 Hz, with $p<.001$. However, at 2000 and 4000 Hz in the left ear, differences between the devices revealed no statistically significant differences between the HA, HA (FM on), and FM device. Statistically significant differences were found between the AMS and all three of the other conditions for all frequencies in both ears, with $p<.001$. Mean left ear output values (in dB SPL) are displayed across frequency (in Hz) in Figure 14; right ear values are shown in Figure 15.

Questionnaire

The questionnaire used in this study can be found in Figure 10. The first set of questions asked participants to rate the difficulty of understanding speech with a particular device, with options of “very”, “moderately”, “somewhat”, or “not” difficult. With the HA condition, six participants experienced moderate difficulty, seven experienced some difficulty, and one experienced no difficulty understanding the HINT material. With the FM device, two participants experienced moderate difficulty, eight participants experienced some difficulty, and four experienced no difficulty. With the AMS device, one person reported the HINT was very difficult, nine experienced moderate difficulty, two experienced some difficulty, and two experienced no difficulty.

For the remaining questions, participants were asked what they did or did not like about the devices as well as whether they would be interested in trying out any of the devices. Six participants expressed interest in pursuing the remote microphone technology, six were not interested, and two were unsure whether they would pursue remote microphone technology. Open-ended responses from participants included statements such as, “There was a hiss with the Bluetooth but no issues with the FM. The FM was clearer.” Another participant noted, “The FM would be the one I would consider taking out into the real world”. Many participants expressed statements similar to these. A statistical analysis of the data was not performed due to the fact that the questionnaire used in this study was not a standardized.

DISCUSSION

The goal of this study was to compare speech recognition in noise between an FM system and an AMS. To the author’s knowledge, there are no peer-reviewed publications examining the performance of an AMS. Therefore, it is imperative that research explore the avenues of this new technology. Previous studies about speech recognition in noise have focused on optimal hearing aid configurations, such as noise reduction technology or directional microphones. However, with current technology, a promising way to improve speech recognition in noise is with the use of a remote microphone via an FM or AMS system.

Research has shown that hearing aids will improve the ability to communicate for a person with sensorineural hearing loss (Kochkin, 1992; Weinstein, 1996; Kricos et al, 2007). However, since hearing aids alone can fail to adequately provide sufficient assistance in the presence of background noise, ALDs offer the potential for the listener to improve the SNR. FM systems, one type of ALD, are well-known for their ability to improve speech recognition in noise. However, few adult patients are realistically fit with FM systems. Crandell and Smaldino (2000) estimate that less than 5% of adults who wear hearing aids are also fit with FM systems. This is noteworthy considering the fact that FM systems have the ability to improve the SNR in noise so that it is comparable to the speech recognition performance in quiet (Boothroyd, 2004). In this study, the FM condition not surprisingly outperformed the hearing aids alone condition. However, the difference in mean RTS between the two remote microphone technologies, FM and AMS, was unexpected.

Initially, it seemed likely that the FM and the AMS would perform equally as well because both technologies utilize a remote microphone in order to improve the SNR. However, this was not the case. While both the FM and AMS conditions consistently outperformed the HA alone, the AMS in fact performed significantly better than the FM. This means that the RTS for the two remote microphone technologies were statistically significant from each other and the HA alone condition. In a study by Lewis et al (2004), which also used an adaptive HINT procedure to evaluate FM speech recognition in noise, mean RTS values were reported as -18.0 dB and -19.8 dB for two different test sites. These values indicate a much better SNR than the

FM values reported in this study. In fact, they are also better than the scores reported for the AMS in this study.

There are a few possible explanations for this difference in mean RTS values. First of all, the two studies used different transmitters. This study used the Phonak Inspiro, which uses a lapel directional microphone most commonly used in a school setting. The Lewis et al (2004) study used a microphone setting called SuperZoom on the TX3 HandyMic, which offers the maximum level of noise reduction by not amplifying at the rear and sides. On the other hand, this study kept the FM settings at the default position, which maintains the hearing aid microphones in the enabled position without any attenuation. In Hawkins (1984), an FM advantage of 15 dB was seen over the HA alone condition. However, he discovered that this difference dissipates as the hearing aid microphones are increasingly less attenuated.

Maintaining the environmental hearing aid microphone while using the FM will limit much of the advantage that the FM presents over using the hearing aids alone. While it would have been possible to apply maximum attenuation to the hearing aid microphones for the FM condition and potentially achieve a lower SNR, it is clinically relevant to evaluate how the devices perform without adjustment. In this study, minimal changes were applied to the settings of the devices. The changes that were made in this study include: adjustments to the gain of the hearing aids per real ear measurements, copying settings from speech in noise to the FM and AMS programs in the Phonak Target software, disabling SoundRecover, and adjustments to the volume of the Inspiro in order to match the output of the hearing aids during test box measurement as closely as possible.

It should be noted that there are several significant differences between the settings of the FM and the AMS devices. For example, the AMS default setting for the environmental hearing aid microphone attenuation is at -6 dB. Keeping in mind that the FM default setting is 0 dB of environmental hearing aid microphone attenuation, adjusting the microphones in the FM program to match the AMS program could allow for a correction of as much as 6 dB to the FM mean RTS score. This correction factor would establish more similar mean RTS values for the FM and AMS, with the AMS only outperforming the FM device by 1.05 dB SNR. The likelihood that the environmental hearing aid microphones could lower the SNR this dramatically is possible, although not likely.

To help streamline these potential variables regarding why the AMS outperformed the FM system, the subjective feedback from the participants was very informative. For example, several participants noted a bothersome echo with the AMS, which could indicate a difference in the delay of the two devices. Many participants believed that there was a delay with the AMS because their voices seemed to echo. According to Agnew and Thornton (2000), a delay of 10 ms is bothersome to a hearing aid wearer 90% of the time. That study also noted that their participants found a time delay much less noticeable when the person wearing the hearing aids spoke more rapidly. It would have been interesting to note whether this was also the case for the participants in this study. However, according to a Phonak representative, the time delay of the FM and the AMS is about the same (Dan Stover, personal communication).

Another difference between the FM and AMS technologies is the directionality of the remote microphones. The lapel microphone of the Inspiro is directional and is sensitive to placement relative to the desired speech signal. On the other hand, the RemoteMic is omnidirectional and its microphone is not as sensitive to placement relative to the desired speech signal. The setup for the remote microphones of both technologies was exactly the same because of this difference in microphone directionality. However, considering the sensitivity of the FM remote microphone, it would be interesting to see how the FM would perform in an even more realistic setting. For example, if the microphone were positioned so that the microphone pointed up toward the ceiling rather than directly at the speaker, this could have been more realistic and akin to a speaker clipping the lapel microphone on a shirt. However, it is still unlikely that the microphone placement pointed directly at the speech signal could provide such a large discrepancy between the two devices. In fact, Hawkins (1984) noted that an FM system that offers a directional remote microphone as opposed to an omnidirectional microphone provides an improved SNR.

The difference in mean RTS scores between the AMS and FM might be explained through the results of the test box measurements. The most noticeable difference is the much higher gain that the AMS provided in the low frequencies at 250, 500, and 750 Hz. At these frequencies, the AMS provided significantly more gain than the FM. The feedback from participants corroborated this point. For example, one participant described a constant "hissing" sound with the AMS, which was likely additional low frequency amplification that this person was not used to hearing. To contrast, this person experienced no issues with the FM and in fact noted that speech seemed clearer with the FM. It should be noted that the FM followed the output of the hearing aids so closely that there were no significant differences between the conditions of HA, HA + FM on, and FM. On the other hand, the AMS provided more than 20 dB of gain at 250 Hz and 10 dB of gain at 500 Hz. At 750 Hz, a statistically significant difference was seen from the AMS in comparison to the other test box measurements; however, this difference amounted to approximately 4 dB and may not be clinically relevant. When hearing tests are performed and compared to previous tests, a difference of 5 dB between one test and another test is believed to be due to test-retest differences (Stuart et al, 1991). Finally, it was possible that the significant deviation in gain with the AMS from the HA settings could have resulted in poorer speech recognition. However, this deviation did not appear to negatively affect the speech recognition ability of the participants.

Other differences between the HA and AMS gain measures can be seen in the high frequencies, most notably at 3000 and 4000 Hz. Although these differences were not found to be statistically significant, the average gain measures showed a 10 dB or greater gain with the AMS device. Therefore, these differences could still equivocate to clinically relevant findings. In fact, despite the fact that only statistically significant differences were found between the HA and the AMS in the low frequencies, the AMS consistently provided more gain throughout the entire frequency spectrum. Therefore, it is possible that the AMS could have outperformed the FM system because the FM system very closely followed the gain measures of the hearing aids, but the AMS device deviated from the gain measures of the hearing aids by providing additional gain at 3000 and 4000 Hz.

Although statistical significance for speech recognition could be seen using the HINT, this was not the case for the evaluation of noise tolerance with the ANL. The ANL procedure applied in this study saw no statistically significant differences between the three conditions. The hearing aids and the FM system both offer noise reduction technology as well as directional microphones; the AMS does not offer these two features. Some studies have indicated that it may be possible to achieve an ANL improvement of 3 to 4 dB with directional microphones and noise reduction technology (Freyaldenhoven et al, 2005; Mueller et al, 2006; Kim and Bryan, 2011). It is possible that this improvement existed for this study; however, this is unclear because no comparisons were made between hearing aids in a directional versus omnidirectional mode. The AMS is an omnidirectional remote microphone; however, it operates in conjunction with the directional microphones of the hearing aids. Therefore, it is difficult to say how this study's results were affected by directional microphone technology.

Despite the fact that the differences between the three conditions were not statistically significant, the mean score while using the FM system, 7.71 (SD=7.84), indicated a borderline more successful hearing aid user. Nabelek et al (2006) described the ANL scores in three categories: participants whose ANL score is less than 7 dB are likely to become successful and compliant hearing aid users, those whose score is greater than 13 dB are likely to have poor hearing aid compliance, and participants whose score is between 7 and 13 have an unreliable device prediction. The HA and AMS conditions both fall within the unreliable device prediction pattern at 11.14 (SD=9.21) and 11.57 (SD=9.32), respectively. This finding potentially could mean that some patients could be more willing to wear a hearing aid when coupled with an FM system. However, there is much uncertainty around this suggestion.

One limitation with this study is that participants were not offered the option of taking home any of the devices. Therefore, participants were not able to learn how to use the devices in real-life situations. Allowing the participants to take home the different devices would likely have led to more informative feedback regarding their thoughts on the sound quality of the devices. Additionally, although all participants were fit using real-ear verification, it is likely that some participants would perform better after making adjustments to the hearing aids. Clinically, patients provide subjective information to the audiologist, who then in turn can make adjustments to provide a better listening experience for the hearing aid user. This study could improve with a design that allowed for devices to be used in the real-world and could thereafter implement the hearing aid user's feedback into the programming of the devices.

Another limitation with this study involves the ANL test setup. This study used only one speaker for both noise and speech. The remote microphone technology may have demonstrated an advantage given a speaker arrangement that separated the desired and competing signals. In this way, the remote microphones of the AMS and FM would directly face the speech signal and the noise would be directed to the sides of the participant's head at 90° and 270°. The primary reason why this setup was not established was because the side speakers used in this study did not allow for remote adjustment of volume. However, it may have been possible to achieve ceiling effects with this setup. Additionally, this study could have benefited from participants self-reporting how often they wear their personal hearing aids. This would have allowed for some comparison between self-reported hearing aid usage and the ANL results achieved from this study.

A final consideration regarding this study involves future studies that might expand upon evaluating the AMS technology. For example, a different speaker arrangement could be implemented. It would be a more realistic experience for a participant to be tested in noise that comes from all angles, and not just from the sides of the head at 90° and 270°. Additionally, the much newer Roger system could be added as a condition with which a comparison could be made to AMS technology. As was previously mentioned, this study would benefit from the opportunity to allow participants to take home their devices. Finally, future studies should consider compensating for the tendency of the AMS to provide additional low frequency gain. Maintaining a similar frequency output across all of the devices would eliminate a variable in the comparison of the three conditions.

CONCLUSIONS

The AMS outperformed the FM device while examining speech recognition in noise. One of the most likely reasons for this is because participants were tested in the default settings for devices, and the hearing aid microphone attenuation is different for the AMS and FM systems. The AMS automatically applies -6 dB of attenuation while the FM system does not apply any attenuation. Another reason for this difference is that the AMS provides an overall additional gain, especially in the low frequencies. The ANL was also analyzed in this study, and the score for the FM technology indicated a greater noise tolerance. However, no significant differences were found between the three test conditions of HA alone, an FM system, and an AMS device. Sound quality judgments in this study showed that the majority of participants from this study preferred the FM over the AMS because they were bothered by the echo and unnatural sound quality they experienced while fit with the AMS.

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Table 1. Descriptive information for the 14 participants

Participant	HA experience (in years)	Gender	Age
1	5	M	73
2	4	F	82
3	10	M	56
4	7	F	57
5	20	F	83
6	10	F	66
7	7	M	72
8	23	F	83
9	5	F	85
10	9	F	74
11	11	M	81
12	8	F	70
13	17	M	77
14	8	M	61

Table 2a. Means and SD of the left ear for test box measures completed using the Audioscan Verifit

		250	500	750	1000	1500	2000	3000	4000	6000
HA	Mean	47.71	67.78	71.93	77.71	80.07	81.07	86.79	88.93	56.93
	SD	11.32	10.07	8.38	7.99	7.82	5.98	4.73	3.93	6.18
HA (FM on)	Mean	45.85	67.50	71.71	77.35	80.00	21.00	86.57	88.86	56.50
	SD	10.68	9.73	8.11	7.89	7.59	5.74	4.78	3.88	6.16
FM	Mean	52.50	64.50	71.50	79.14	82.57	82.71	95.14	90.86	51.71
	SD	10.49	7.83	8.14	7.93	6.73	4.71	2.96	5.05	6.02
AMS	Mean	74.36	78.64	77.57	82.29	84.79	88.29	95.14	99.93	62.43
	SD	7.68	6.22	7.32	6.98	5.98	3.73	2.96	3.10	10.14

Table 2b. Significance values of the left ear for the test box measures completed using the Audioscan Verifit

	250	500	750	1000	1500	2000	3000	4000	6000
F	84.30	55.28	80.33	63.54	34.54	80.24	116.23	147.47	24.83
df(device)	3	3	3	3	3	3	3	3	3
df(device error)	39	39	39	39	39	39	39	39	39
sig.	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001

Table 3a. Means and SD of the right ear for test box measures completed using the Audioscan Verifit

		250	500	750	1000	1500	2000	3000	4000	6000
HA	Mean	49.14	70.00	73.64	80.43	82.07	80.71	84.64	87.14	55.64
	SD	13.08	11.92	8.53	7.69	7.12	6.13	6.98	4.09	5.77
HA (FM on)	Mean	48.86	69.50	73.21	80.29	81.86	80.21	84.50	86.93	55.29
	SD	13.13	12.36	8.51	7.15	6.88	6.02	7.05	4.48	5.66
FM	Mean	55.21	68.43	74.42	82.57	82.57	83.00	87.36	89.57	51.43
	SD	8.89	10.06	8.48	7.22	7.22	5.88	6.65	4.22	4.70
AMS	Mean	75.50	80.14	77.86	84.21	84.21	87.36	94.29	99.21	61.21
	SD	8.42	6.86	6.67	6.35	6.35	5.05	6.49	3.85	9.45

Table 3b. Significance values of the right ear for the test box measures completed using the Audioscan Verifit

	250	500	750	1000	1500	2000	3000	4000	6000
F	58.84	24.99	32.03	58.87	59.26	83.73	167.11	180.46	27.6
df (device)	3	3	3	3	3	3	3	3	3
df (device error)	39	39	39	39	39	39	39	39	39
sig.	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001

Figure 1. Audiogram reporting the mean and ± 1 SD for combined left and right ear pure-tone thresholds (dB HL)

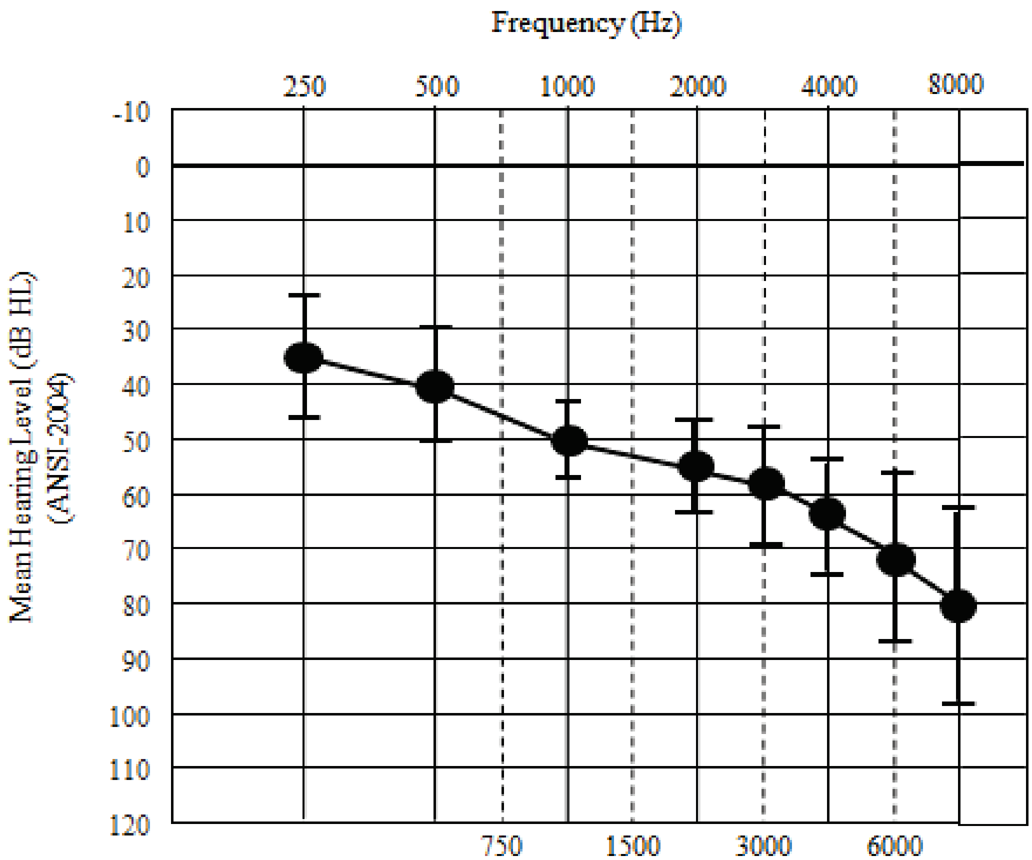

Figure 2. Larson-Davis 706 dosimeter

Source: Hawkins, Erin F., "Comparison of hearing levels of college music and non-music majors: Does rehearsal noise affect hearing health?" (2013). Independent Studies and Capstones. Paper 678. Program in Audiology and Communication Sciences, Washington University School of Medicine http://digitalcommons.wustl.edu/pacs_capstones/678. Used with permission from Erin Hawkins.

Figure 3. Speaker setup with center speaker at 0° azimuth and side speakers at 90° and 270° azimuth

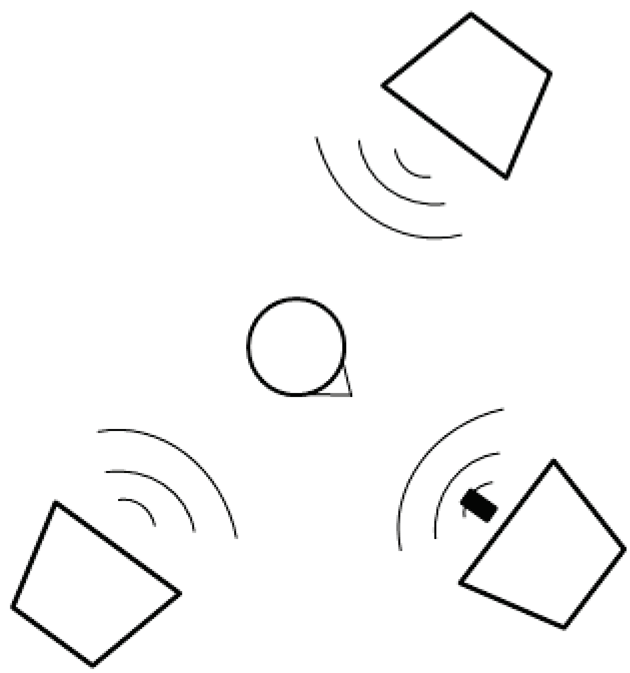

Figure 4. Bolero Q-90 hearing aids with attached receivers

Figure 5. Phonak Inspiro with lapel microphone

Figure 6. Phonak RemoteMic

Figure 7. Phonak ComPilot

Figure 8. Mean difference and ± one SD between NAL-NL1 and measured REIG

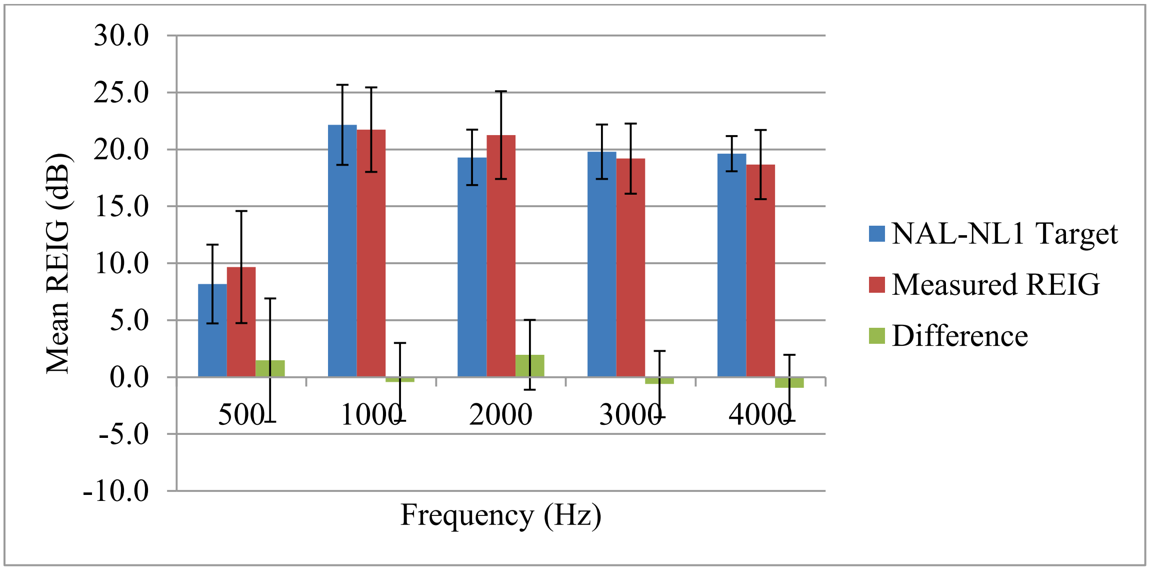

Figure 9. Output (in dB SPL) for one participant's left HA, FM, and AMS as shown in the test box measurement.

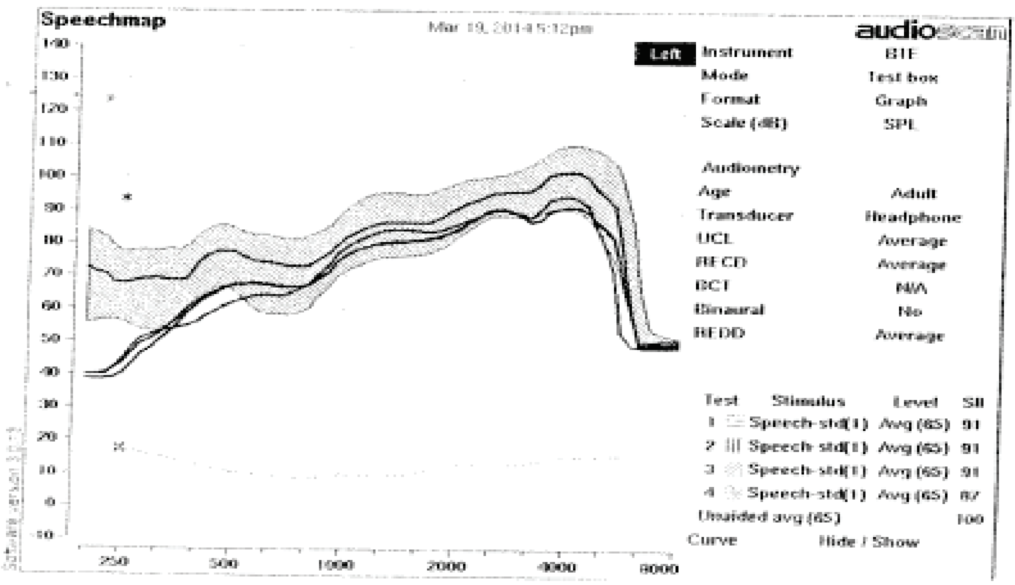

Figure 10. Questionnaire

Perceived-Benefit Questionnaire Administered after Test Session

	Very	Moderately	Somewhat	Not
How difficult was it to understand the test material with just the hearing aids?				
How difficult was it to understand the test material with the first device?				
How difficult was it to understand the test material with the second device?				

What do you like about the devices?
What do you dislike about the devices?
Would you be interested in trying out any of these devices in your daily life?

Figure 11. Mean and ± 1 SD for HINT SNR scores (in dB) for the three listening conditions: hearing aids alone, FM device, and AMS device.

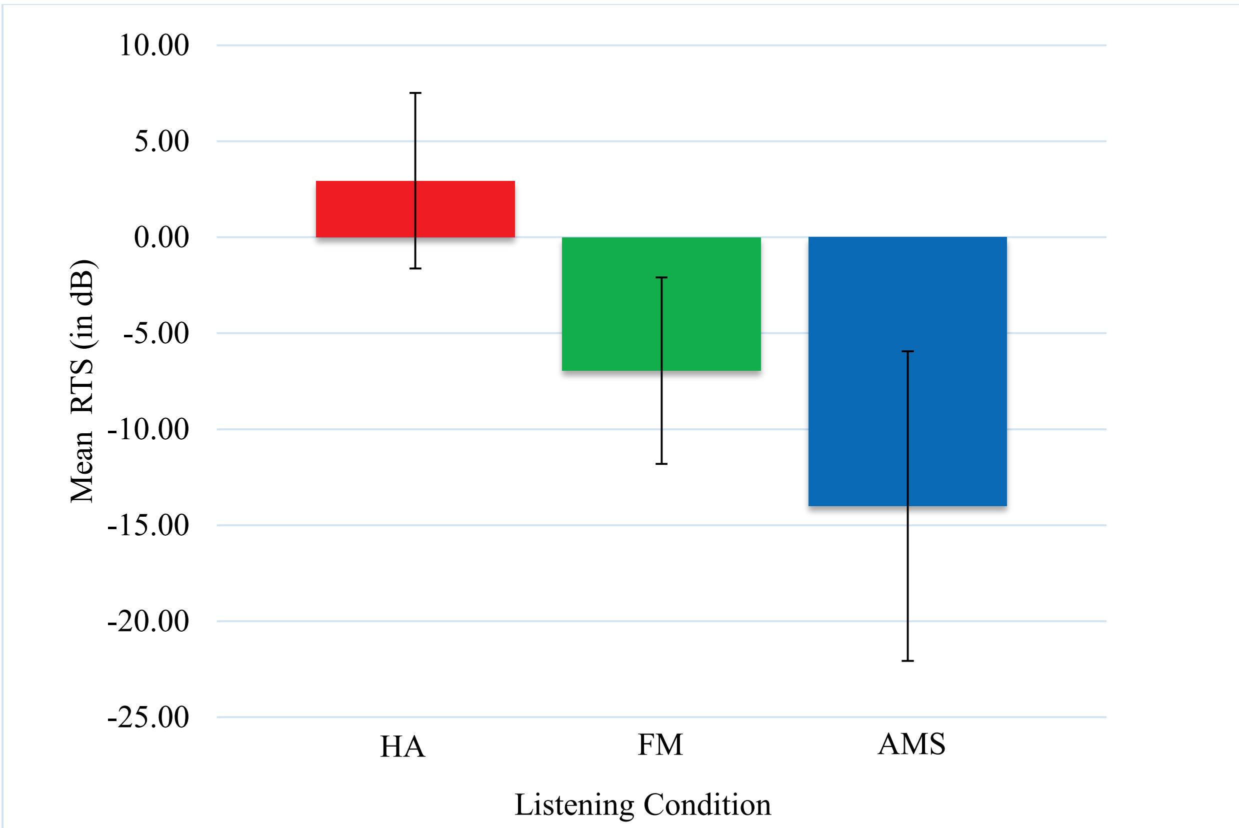

Figure 12. Improvement in speech recognition in noise with FM and AMS in comparison to HA condition

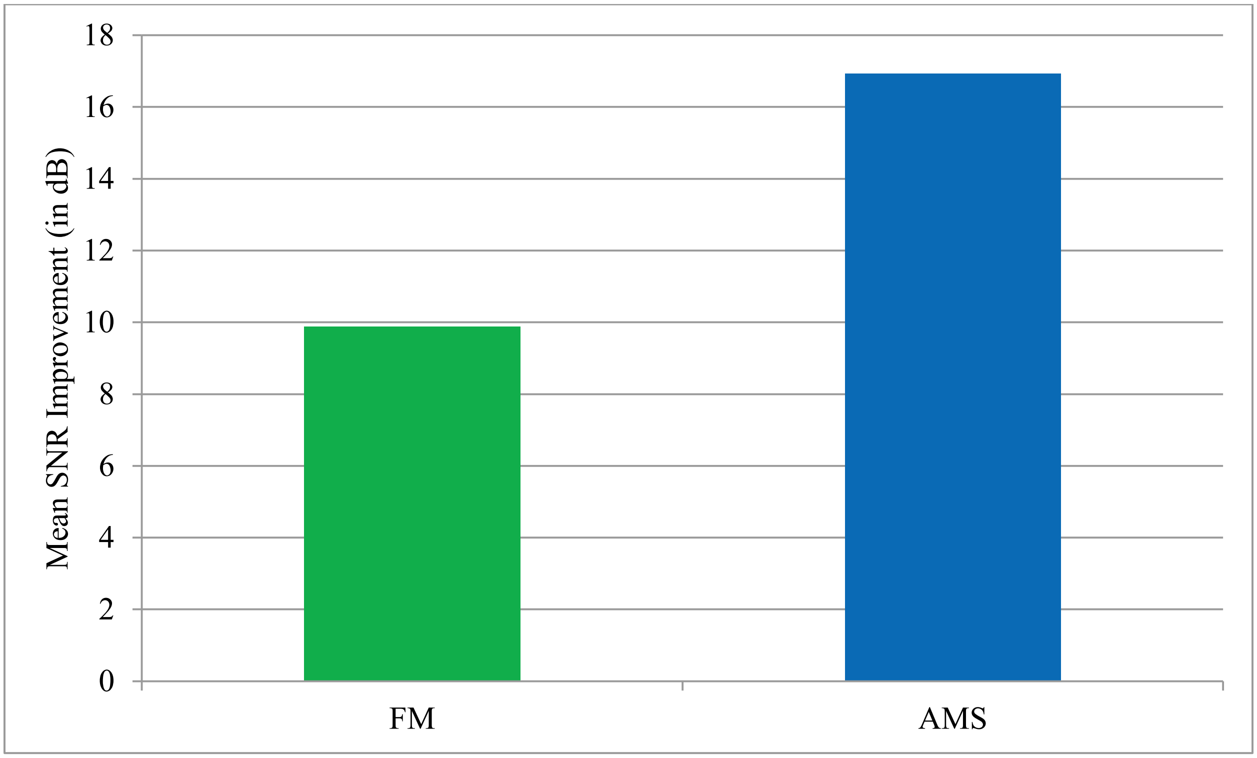

Figure 13. Mean and ± 1 SD for ANL scores for listening conditions of with hearing aids alone, FM device, and AMS device

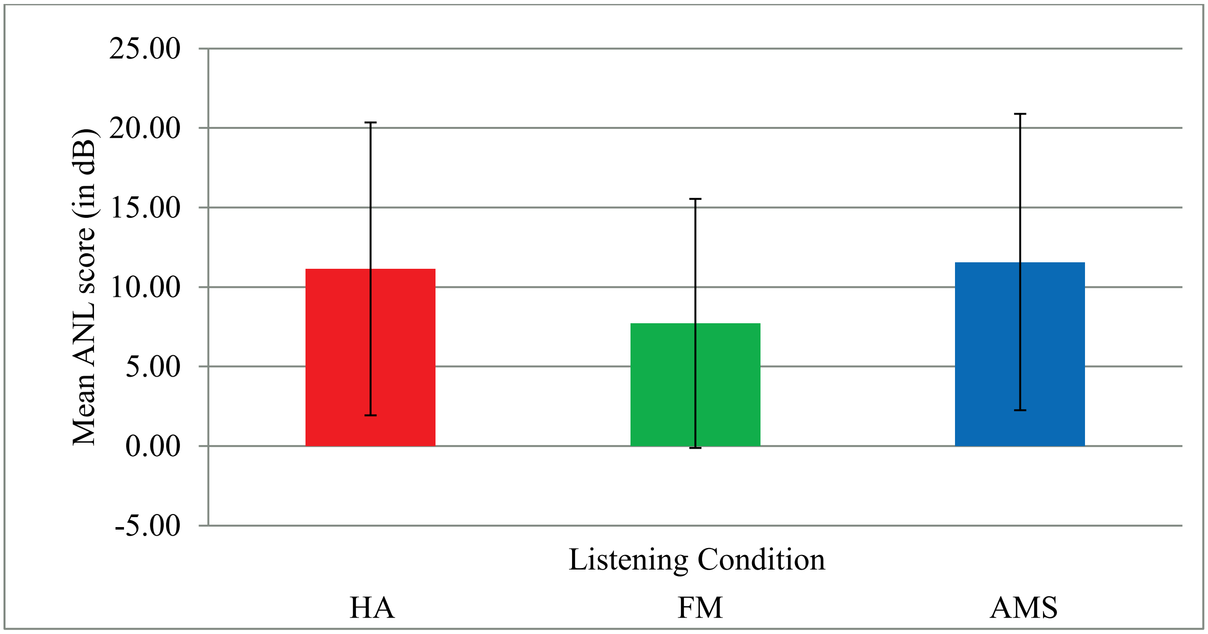

Figure 14. Mean left ear output values (in dB SPL) across frequency (in Hz) for Audioscan test box measurements

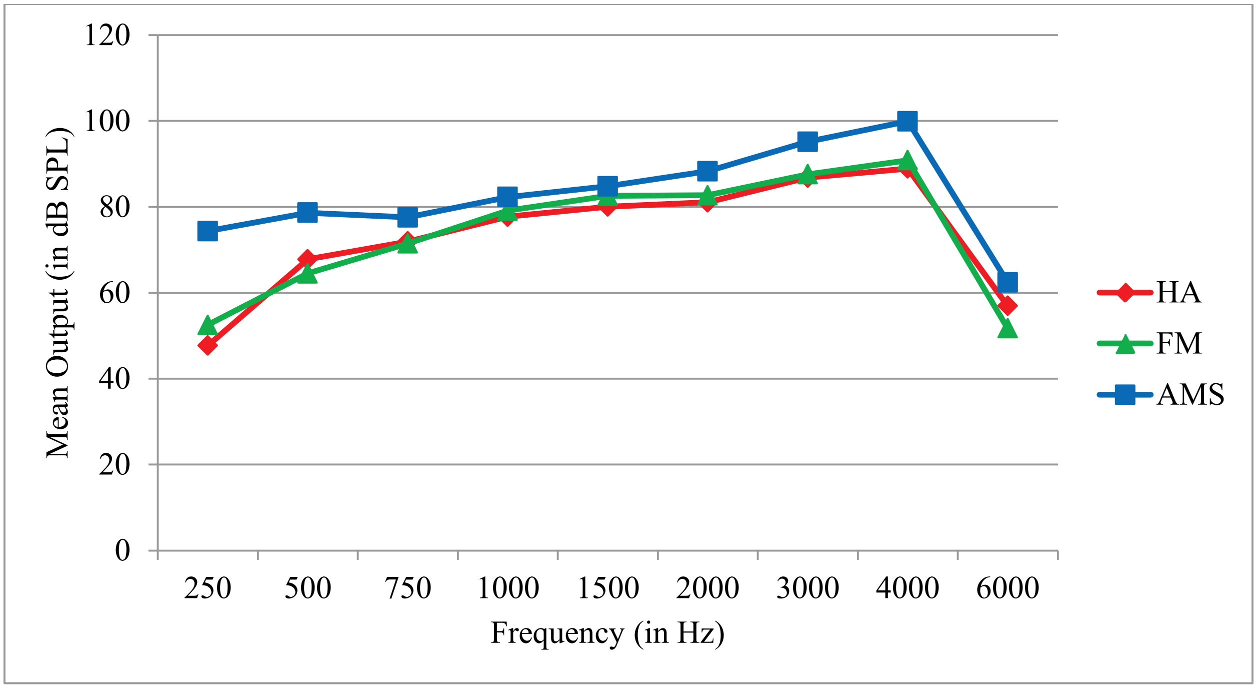

Figure 15. Mean right ear output values (in dB SPL) across frequency (in Hz) for Audioscan test box measurements